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OBSERVATIONS OF THE SUN, AN ULTRAVIOLET VARIABLE STAR

DONALD F. HEATH

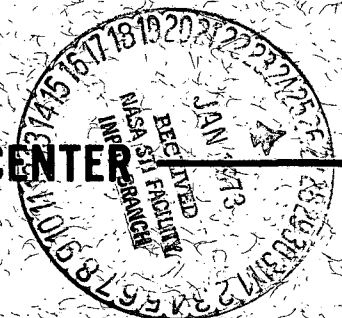
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OBSERVATIONS OF THE SUN,
AN ULTRAVIOLET VARIABLE STAR

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OBSERVATIONS OF THE SUN, AN ULTRAVIOLET VARIABLE STAR

Introduction

The history of past attempts to establish a correlation between earth-based observations of solar activity and terrestrial phenomena has been long and varied. This frequently has led to the suggestion that perhaps the sun might be classified as an ultraviolet variable star. Variability in the ultraviolet solar irradiance had been observed for H Lyman alpha and the shorter wavelengths which are responsible for the production of the ionosphere. Also it is well known that there are variations associated with flares, solar rotation, and the eleven-year sunspot cycle. Whether or not this variability extended up to the visible was not known. This is not surprising. If one assumes that one is observing the radiation from a blackbody at a temperature T , then the corresponding enhancement, $\Delta F/F$ for a given ΔT is $\frac{1}{F_\lambda} \frac{\Delta F}{\Delta T} = \frac{1}{T^2} \frac{1.44 \times 10^4}{\lambda (\mu m)}$ which has a λ^{-1} dependence. An even more fundamental problem associated with earth based observations of the sun in the middle ultraviolet and the visible is that they are complicated by a highly variable atmospheric aerosol distribution which may change significantly over the time period of observations. Under these changing atmospheric conditions, the extrapolation to zero atmosphere may not be valid.

The uncertainty as to whether or not the sun is a variable star in that region of the ultraviolet which is absorbed in the mesosphere and stratosphere led to an experiment with the acronym MUSE, Monitor of Ultraviolet Solar Energy. The experiment was first flown on an Aerobee rocket in August 1966

and subsequently on Nimbus 3 and 4 in April 1969 and April 1970 respectively. The basic philosophy behind the design of the experiment was to provide an instrument which would not require a solar pointing mechanism and at the same time would be capable of high radiometric accuracy for long periods in space.

Instrumentation

The basic experiment shown in Figure 1 consisted of a digital solar aspect sensor to provide the angle of solar illumination of the sensors, and five broad band photometers to provide coverage of the sun from 1135 to 3000Å. A detailed description of the experiment and its absolute radiometric calibration may be found in Heath (1972a), the Nimbus 3 Users Guide (1969), and the Nimbus 4 Users Guide (1970). The experiment was located in the -X direction (180° from the spacecraft velocity vector) between bays 9 and 10 of the Nimbus Sensory ring. The 3-axis earth oriented Nimbus 3 and 4 spacecraft were put into sun-synchronous, 10° retrograde (near polar), circular orbits at an altitude of 1100 km. The ascending node occurs near local noon. Under these circumstances the sensors (90° field of view) are illuminated at near normal incidence at the northern terminator. The sun comes into the sensor field of view nominally 45° from the northern terminator, and remains until the sun is occulted by the earth. The sun is observed for about 20 minutes of each 107 minute orbit.

The pass band of the sensor's response is determined by the short wavelength cut-off of a uv transmitting material and the long wavelength rejection by photocathodes with varying degrees of "solar blindness" or cathode work functions. The photocathode currents are sequentially switched into a four-decade,

linear, range switching electrometer. During every 48 second experiment cycle, calibration currents from Americium 241 ionization current sources are switched into each of the four current decades.

In the analysis of the data one must use the observed sensor current. The sensor current is given by

$$I \text{ (amperes)} = \sum_{\lambda_i} (F_{\lambda_i}) (\Delta \lambda) (T_{\lambda_i}) (Q_{\lambda_i}) (A) (1.6 \times 10^{-19})$$

where F_{λ_i} is the mean solar irradiance at λ_i per unit wavelength interval, $\Delta \lambda$ is the wavelength interval over which the solar irradiance is averaged, T_{λ_i} is the combined filter transmittance, Q_{λ_i} is the photocathode quantum efficiency, and A is the effective photocathode area. The effective area is the product of the geometrical area and a cathode uniformity function relative to the quantum efficiency measured at the center where the calibration is made.

In order to derive the true solar irradiance, F_{λ_i} with the MUSE experiment it is assumed that $F_{\lambda_i} = \alpha f_{\lambda_i}$ where α is a constant over the detector passband, and f_{λ_i} are published values of the solar irradiance. The MUSE detectors have passbands of a few hundred angstroms.

A double monochromator experiment designated Backscatter Ultraviolet, BUV, was also flown on Nimbus 4. A part of its mission was to measure the solar irradiance at 12 discrete wavelengths from 2550 to 3400A with a 10A bandpass.

Observations

The function $\alpha = F_{\lambda} \text{ (observed)}/F_{\lambda} \text{ (model)}$ is given in Figure 2 for the wavelength of the median sensor response for the MUSE experiments. The first was flown on an August 1966 rocket flight which reached an altitude of 210 km. Subsequently the second and third were flown on the Nimbus 3 and 4 satellites (launched in April 1969 and 1970) which are designated by the symbols Δ , \square , \circ . The curves of the sensor responses are contained in Heath (1972a). The crosses, \times , represent observations with the BUV experiment for April 1970. In the derivations of the function alpha the following sources were used for $F_{\lambda} \text{ (model)}$ in the MUSE analysis: Hinteregger, et al., 1964, Detwiler, et al., 1961 and Tousey, 1963. The tabulation by Furukawa, et al., 1967, which had been weighted over a 10A (half-width) triangular slit function was used with the BUV observations. These observations are the basis for concluding that there is a significant 11 year sunspot cycle variation in the irradiance which is an increasing function of decreasing wavelength as one approaches the region of the solar temperature minimum which is observed at about 1600A and marks the transition from photospheric to chromospheric radiation.

One of the great values in satellite experiments is that while the absolute value of an experimental observation may be subject to considerable error, the precision of observations from orbit to orbit is generally extremely high. In the case of the instrumentation used in acquiring the data for this work it was found that the experiment degradation in space could be represented by a linear

relationship between the logarithm of the sensor current and time. The observed degradation may be represented by a series of straight lines whose slope (absolute value) is decreasing with time. An analysis of the degradation of uv systems on Nimbus 3 and 4 satellites has been given by Heath (1972b). The above characteristic has made it possible to detect changes in the solar irradiance with the MUSE experiments of the order of 1% per 27-day solar rotational period.

Examples of the changes in solar irradiance which are associated with the rotation of active regions on the sun are shown in Figure 3 for eight solar rotations. The data are ordered so that the top of the figure represents the solar irradiance originating in the upper photosphere. Continuing downward in the figure to B, A, and 10.7 the source of irradiance progresses upward through the solar atmosphere coming from the region of the solar temperature minimum between the photosphere and chromosphere, and the corona respectively. While there is a good correlation between the uv and the 10.7 cm emission with regards to the location in time of the maxima and minima, the correlation of the enhancements is poor as will be discussed in a succeeding section. A good example may be seen in the maxima which were observed on days 188, 217 and 243. Relative to the enhancement observed on day 217, the predominantly H Lyman alpha enhancements observed with sensor A are larger on days 188 and 243 whereas the converse is true with the 10.7 cm radiation.

The median sensor responses are at 1216A for A, 1770A for B, and 2930A for C. The wavelength interval for 50% of the signal about the wavelength of the median response is 150A for B and 400A for C. About 80% of sensor A signal

is due to H Lyman alpha and about 20% from the region centered around 1600A. The ratio of the 1216A to 1600A contribution varies dependent upon whose published values of solar irradiance are used. See Heath (1972a).

Typically the enhancement in solar irradiance with solar rotation which has been observed with the MUSE experiment has been 25% with sensor A, 6% with sensor B, and less than 1% with sensor C. The variation with the wavelength of the median sensor response is approximately linear if the logarithm of the enhancement is graphed against the wave number (cm^{-1}) of the median sensor response. The three sensors in Figure 3 show a declining level of rotational variability with increasing time past solar maximum of the 11-year cycle which occurred sometime during the last quarter of 1968.

The enhancement $(F_{\text{max}} - F_{\text{min}})/F_{\text{min}}$ per solar rotation observed with sensor A for the period covering 30 solar rotations is shown in Figure 4. The straight line represents a sort of upper bound or envelope of the enhancement with solar rotation. The significant feature here is that there is an indication of an exponential decay with time past solar maximum. Furthermore, within this period there is some evidence of quasi periodic oscillations in the enhancement. The different symbols are used to indicate a persistent clustering about active solar longitudes.

This persistence of active solar longitudes is shown in Figure 5. Each data point indicates the Carrington longitude of the solar meridian on the days when sensor A indicated the solar irradiance, (principally H Lyman alpha) was a maximum. For the most part the maxima appear to originate from two active longitudes which are separated by about 180° in solar longitude. Generally one

can ascertain the time of the maximum to slightly better than ± 1 day for sensor A. This can be seen in Figure 3 for the sensor currents observed at one day intervals.

A major class IIIb optical flare was observed at about the end of the first week in orbit of Nimbus 3. One report indicated that the maximum phase was observed at 2011 U.T. on April 21, 1969 in the light of H alpha. The enhancement observed in the post maximum phase with the MUSE sensor A is shown in Figure 6. The extrapolation of sensor A back to 2011 U.T. yields a flare enhancement of 12% if one assumes an exponential decay in the post flare phase.

Correlations with Other Solar Observations

An important goal of satellite observations is to establish correlations of the uv solar irradiance with earth based measurements which were made during the operational lifetime of the experiment on the satellite. Hopefully one can use these correlations to infer changes in the solar irradiance during those periods when the satellite experiment was not operational. In the succeeding section the MUSE observations from Nimbus 3 and 4 will be compared during the period of overlap in their operational lifetimes, with the solar H Lyman alpha observations on OSO-5, and with the conventional indicators of solar activity.

Similar satellite data on the variability of the H Lyman alpha solar irradiance have been obtained from OSO-5 by Vidal-Madjar, Blamont, and Phissamay (1972). Using the same analysis scheme to obtain the enhancement per solar rotation one observes the correlation between the two experiments as

shown in Figure 6. The enhancement (%) is defined as $100 (F_{\max} - F_{\min})/F_{\min}$. The correlation is reasonably good if one excludes the four MUSE observations for enhancements greater than 30%. The principal difference between the two experiments is that the MUSE sensor A signal contains a significant contribution from the solar irradiance at 1600A while the OSO-5 experiments observations are for a 100A band centered about H Lyman alpha. This difference is probably responsible for the slope being less than one and not passing through the origin. One, however, cannot exclude completely the possibility that the data reduction techniques are involved.

A summary of the simultaneous observations of the solar irradiance from Nimbus 3 and 4 with sensor A is contained in Table 1, which contains the maxima observed between days 100 and 180 of 1970. Apart from the rather large discrepancy (Factor of 2) on day 133 the agreement is excellent. The reason for this discrepancy is not known, however, it is conceivable that the Nimbus 3 sensor A response has been altered due to a spectrally selective space degradation. One would then expect a similar discrepancy in the other observations which is not observed.

The relation between standard indices of solar activity and the sensor A observations of solar irradiance are shown in Figures 8 and 9, for the period from April 1969 to June 1971. Since the sensor A output is due principally to lower chromospheric radiation, one would expect a reasonably good correlation with the calcium plage index which consists of the product of the area and intensity of the plages in the light of calcium which also originates in the lower chromosphere. The correlation between the sensor A observed enhancement and the

calcium plage index is very poor. The same can be said for comparison with the 10.7 cm radiation which is coronal in origin.

A possible explanation for the poor correlation may be that the normal indices of solar activity originate principally from rather localized regions on the sun which cover a very small fraction of the solar disc whereas the variations in irradiance observed with sensor A may come from regions which may cover a significant portion of the solar disc. Hence, one would not expect the correlation to be very good.

Since the time of the maximum in solar irradiance can be determined to slightly better than ± 1 day, a histogram of the time difference between the day of the solar index maximum and the irradiance maximum observed with sensor A may provide additional information on the source of uv activity. This has been done for the calcium plage index (AI), the provisional mean Zurich sunspot numbers, R_z , the 10.7 cm flux, and the daily sum of K_p when ≥ 30 . These histograms are shown in Figures 10-13. It is obvious that the spread is significantly greater than what one would expect if the maximum in sensor A coincided with the maximum of the particular solar index. The ΣK_p is a measure of the perturbation of the geomagnetic field by the solar wind whose transit time from the sun to earth is a nominal 4.5 days.

Quite possibly the spread of the histograms in Figures 10-12 are another indication that source of solar activity observed with the MUSE experiment is spread over a significant fraction of the solar disc.

Discussion

The Nimbus uv solar observations have shown that indeed significant variations do take place in the solar irradiance in the region from H Lyman alpha up to 3000A. One additional period of variability has been observed. An enhancement several times greater than the annual variations was observed with sensor A which appears to have reached a maximum sometime near the spring of 1969 and 1971. This has been discussed in greater detail in Heath (1972a). The real test as to this long period of variability is whether or not it appears in early 1973.

A summary of the observed uv enhancements is shown in Figure 14. The flare associated enhancement formula is from Hall (1972) and is in good agreement with the sensor A data assuming the enhancement is due principally to H Lyman alpha.

The variability which appears to follow the 11-year sunspot cycle seems well established on the basis of three points in time separated by three and one years respectively. This variation has been observed to be greatest for solar radiation which originates in the region of the solar temperature minimum between the photosphere and chromosphere.

In the future an attempt will be made to examine the data in great detail for shorter periods of variability. Most likely periods are those associated with the newly observed short period oscillations (SPO's) which are of the order of five minutes.

Some of the evidence that the source of solar variability observed with the MUSE experiments originates from a significant fraction of the solar disc is as follows: 1) Poor correlations of the sensor A 27-day variability with solar indices which originate in small localized areas on the sun but at nearly the same altitude in the solar atmosphere. 2) A significant difference in time, which equates to solar longitude, between irradiance maxima in the uv and the solar indexes. 3) The apparent existence of two active longitudes separated by about 180° .

An interesting possibility is that the MUSE observations of the variability of the solar irradiance may be related to the total solar magnetic field which is the order of a few gauss. For example it is well known that Alfvén waves can propagate energy along magnetic field lines. This may be a means of producing the enhancements which are observed originating in the lower chromosphere, chromosphere-photosphere transition region and upper photosphere. Consequently one would expect the MUSE observations of solar variability to correlate best with the integrated polar magnetic field. This is an area which will be examined in great detail in the future.

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Table 1

**Simultaneous Observations of the Sensor A Recorded Solar Irradiance
from Nimbus 3 and 4**

$$100 (F_{\max} - F_{\min})/F_{\min}$$

Day Number of UV max (1970)	122.5	133	150	162.5
Nimbus 4	19	23	16	10
Nimbus 3	16	11	13	10

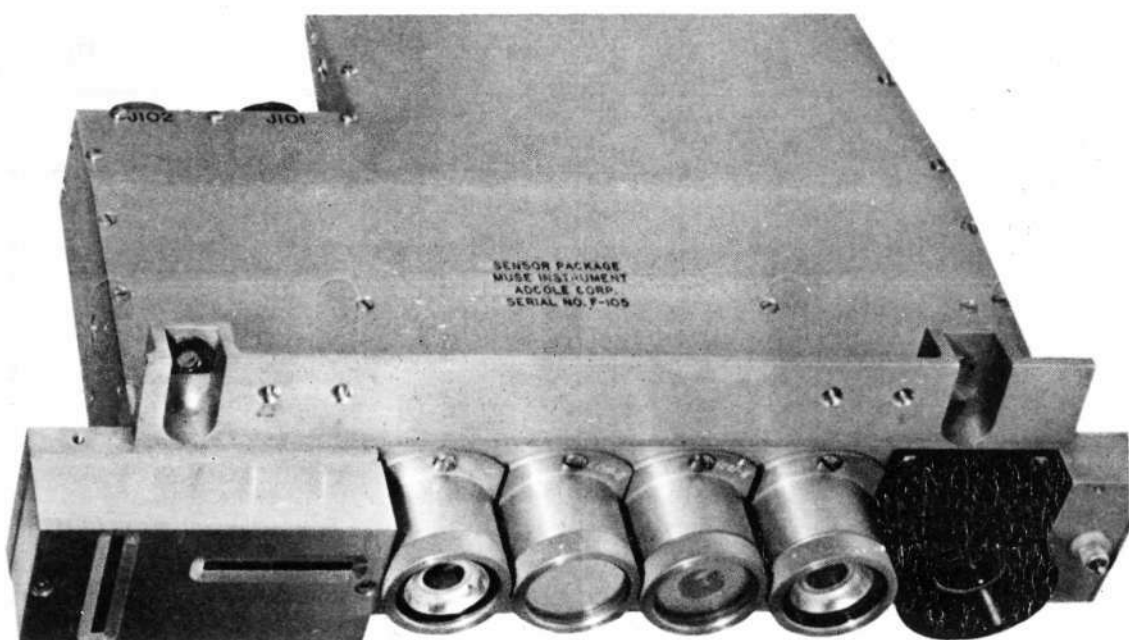


Figure 1. A MUSE sensor package with five co-linear sensors for solar irradiance observations in the 1150 to 3000Å region. Top of instrument contains a digital solar aspect sensor.

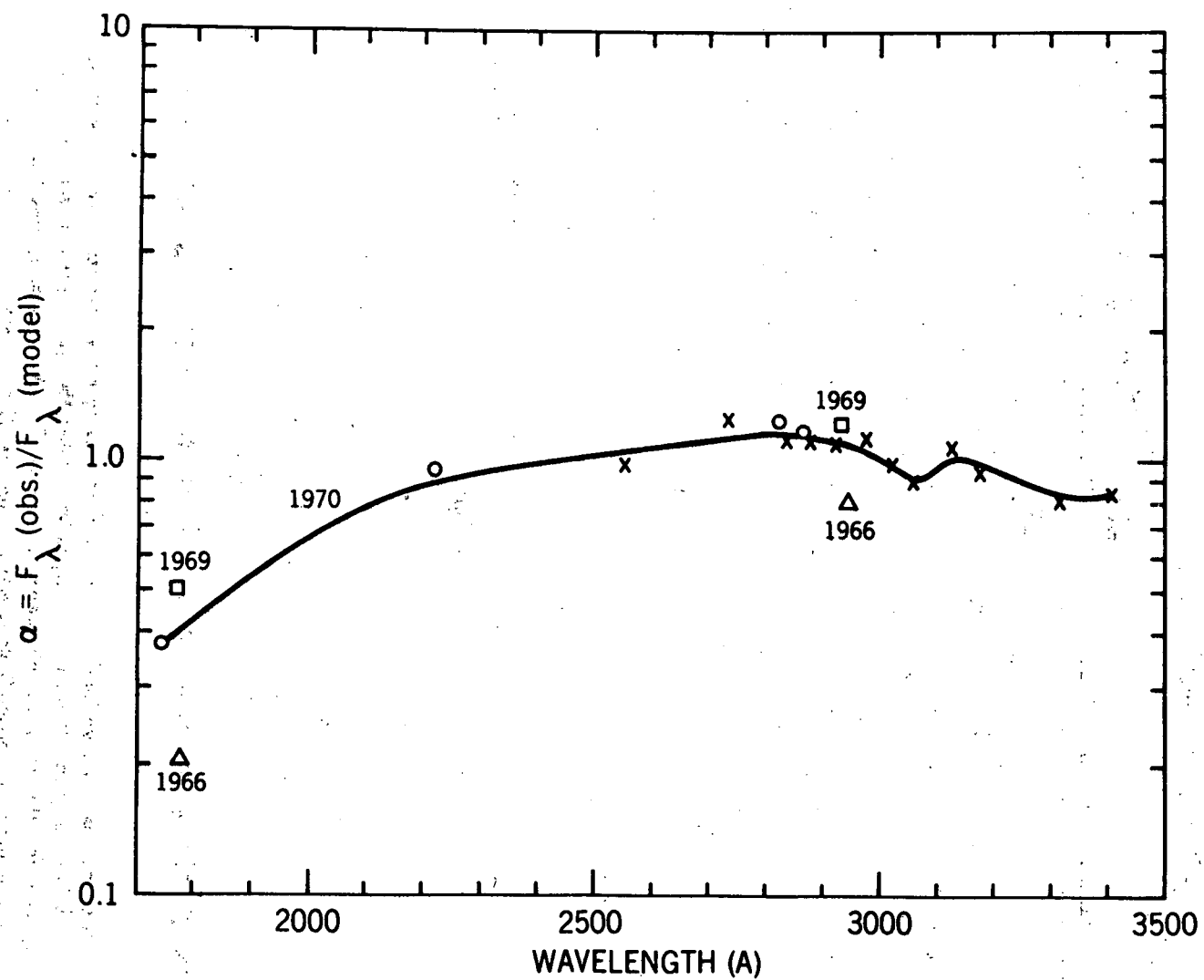


Figure 2. Composite of the solar irradiance normalization function from Nimbus 3 and 4 experiments and a rocket flight indicating a possible long term (11 year) variability.

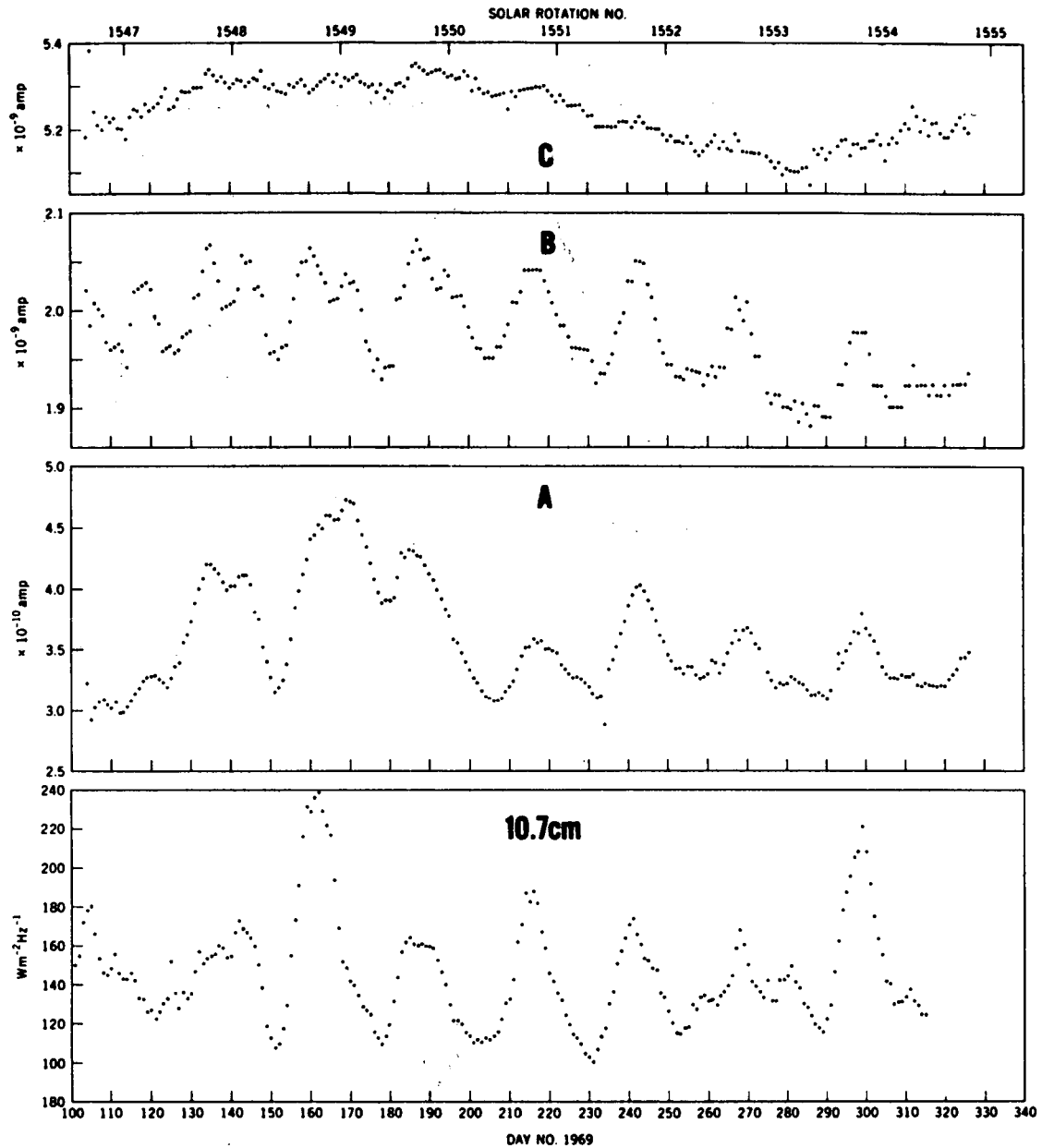


Figure 3. Illustration of solar variability in irradiance arising from the rotation and persistence of active regions on the sun. Moving downward in the figure corresponds to moving upward from the top of the photosphere, sensor C, to the photosphere-chromosphere transition region, sensor B, to the lower chromosphere, sensor A, to the corona, 10.7 uv radiation.

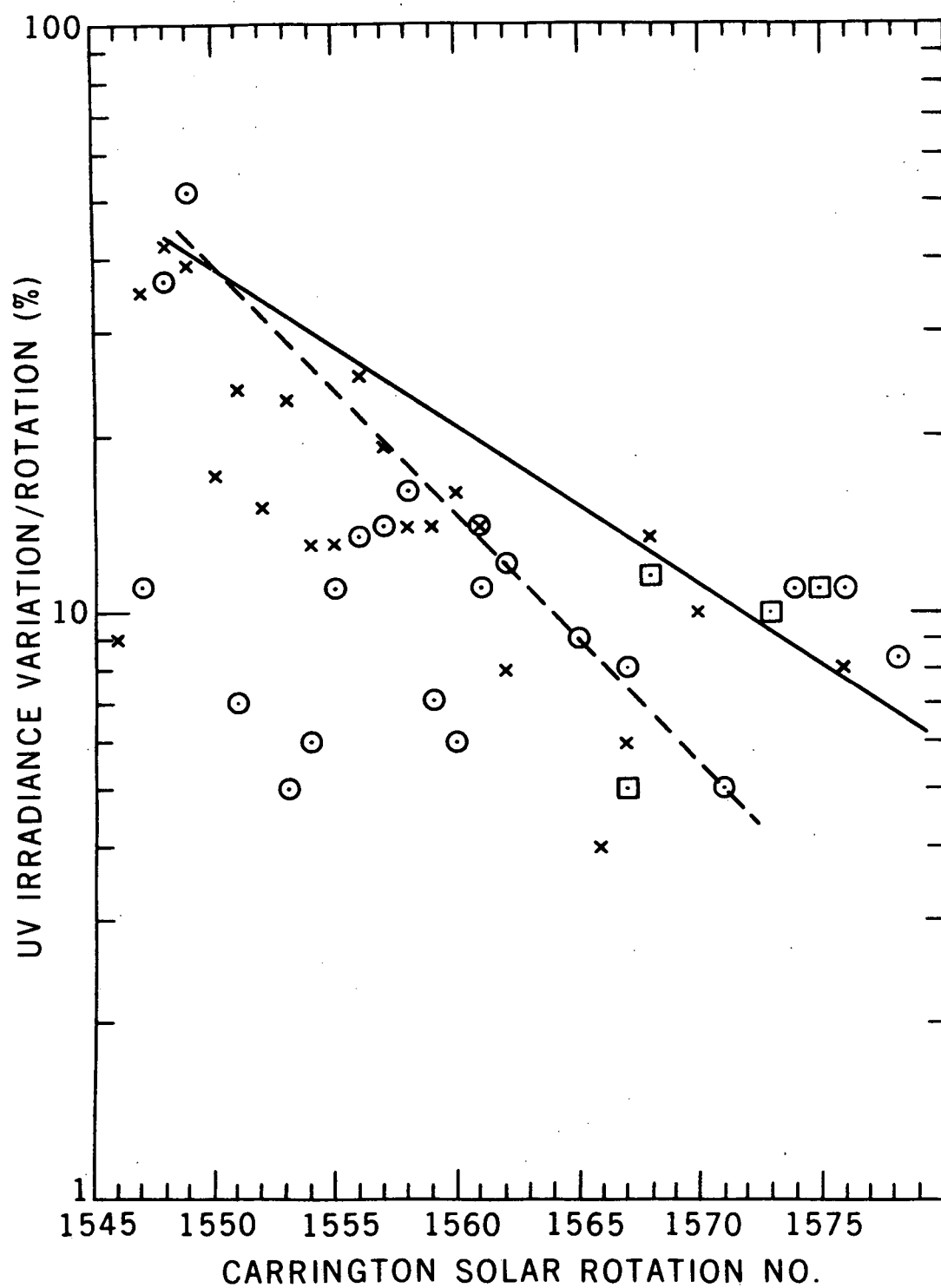


Figure 4. Time variation of the enhancement, $100 (F_{\max} - F_{\min})/F_{\min}$ past solar maximum of the sensor A observed uv activity.

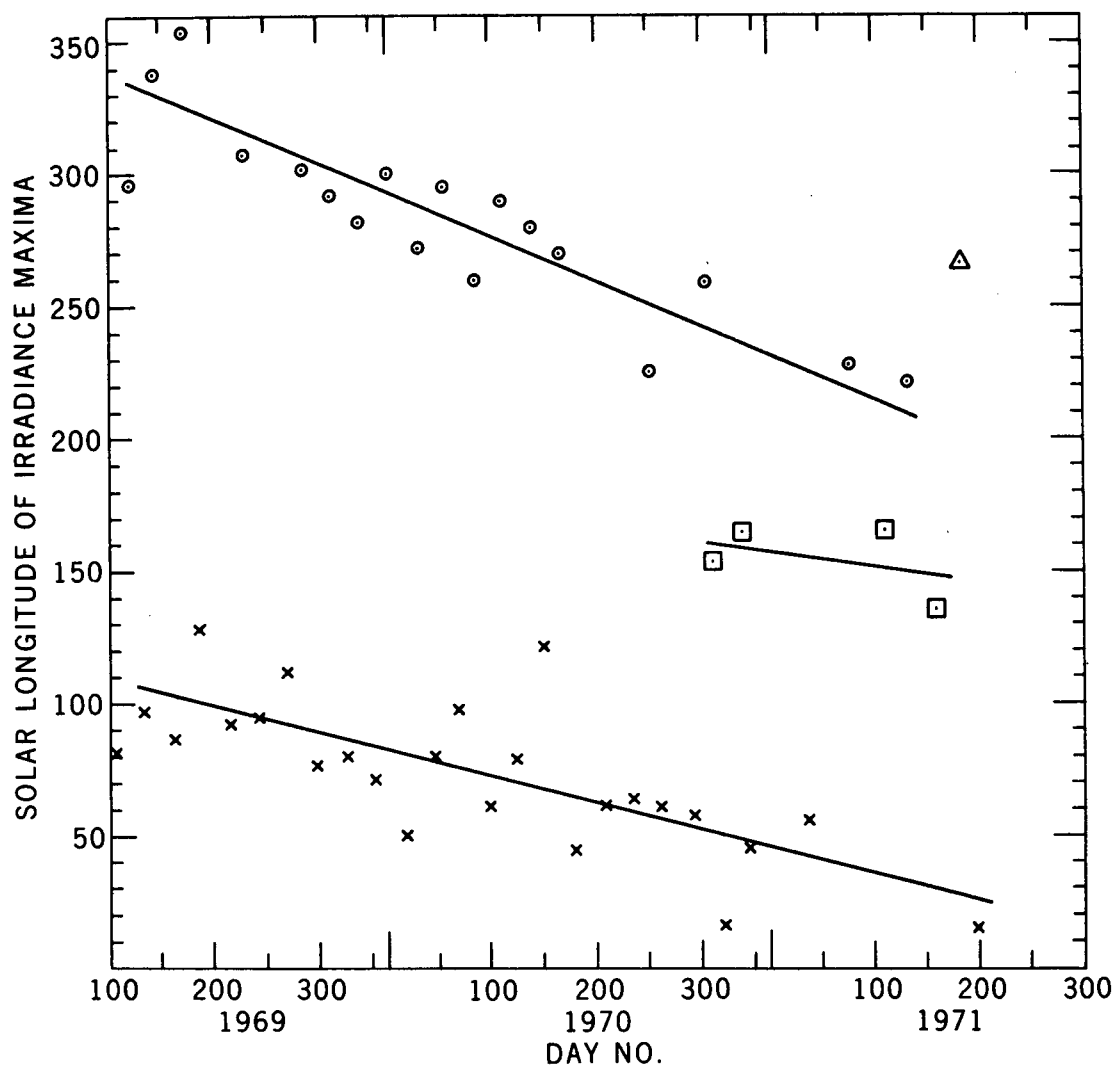


Figure 5. Change in solar longitude of the uv active regions observed with sensor A. The symbols refer to apparent different active regions on the basis of their persistent clustering in longitude. It is assumed that the solar longitude of the active region coincides with the solar meridian at the time when the sensor A signal is a maximum.

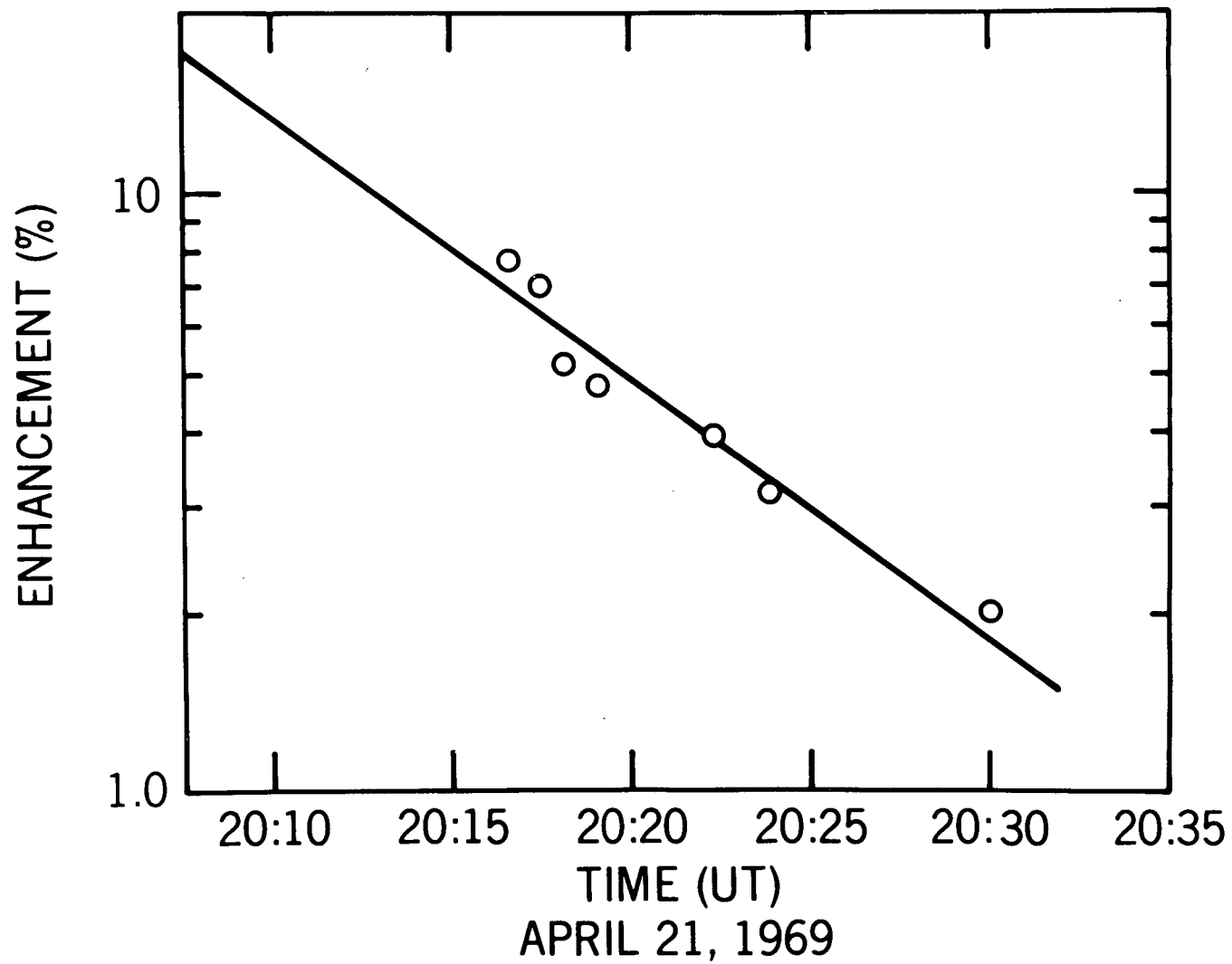


Figure 6. Extrapolation of the sensor A observed enhancement of a class 3 optical flare back to the time of the maximum in the light of H alpha.

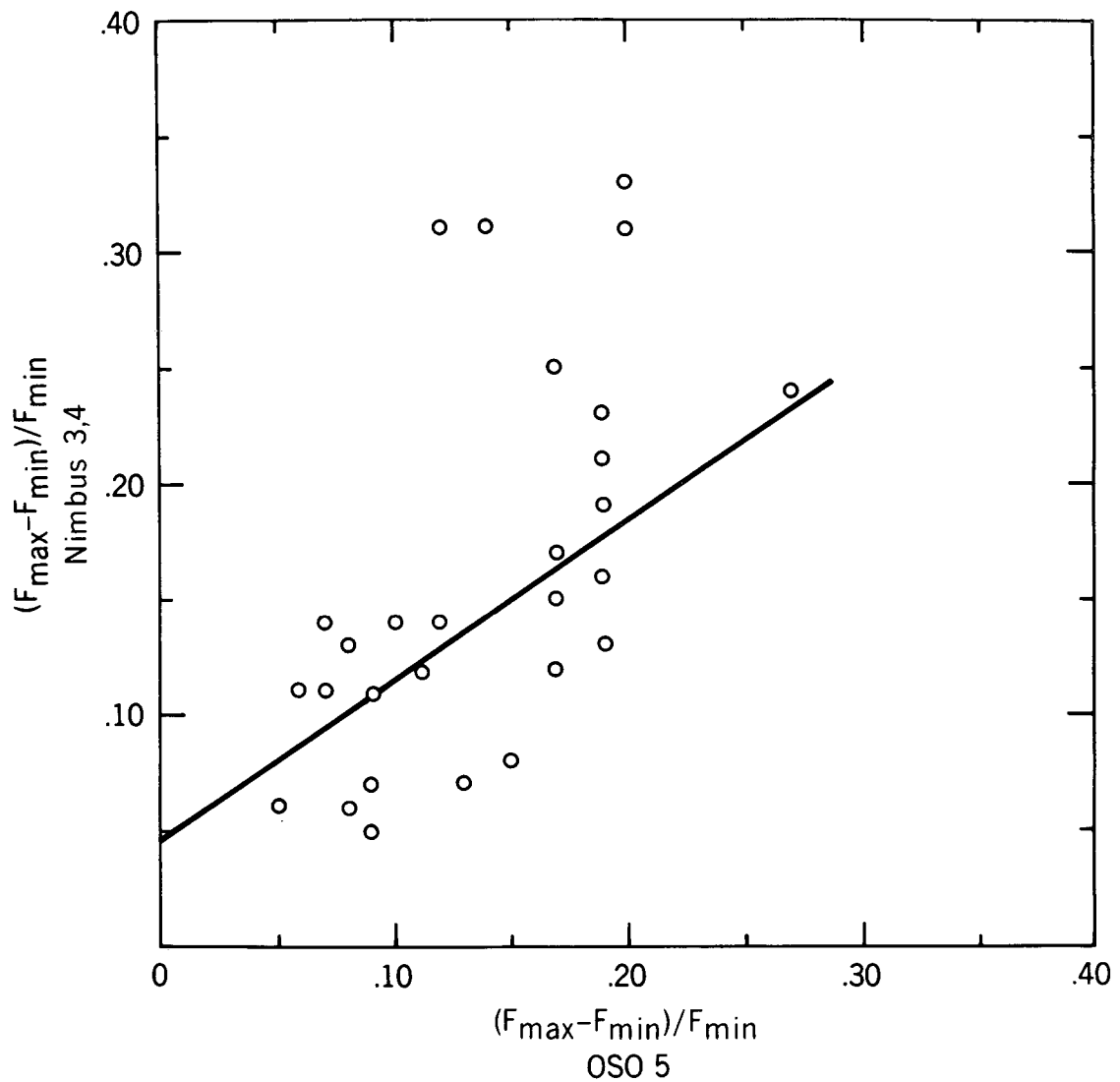


Figure 7. Correlation of the signal enhancement of the Nimbus 3 and 4 MUSE sensor A observation of H Lyman alpha plus 1600A radiation with that from OSO-5 for a 100A band centered about H Lyman alpha.

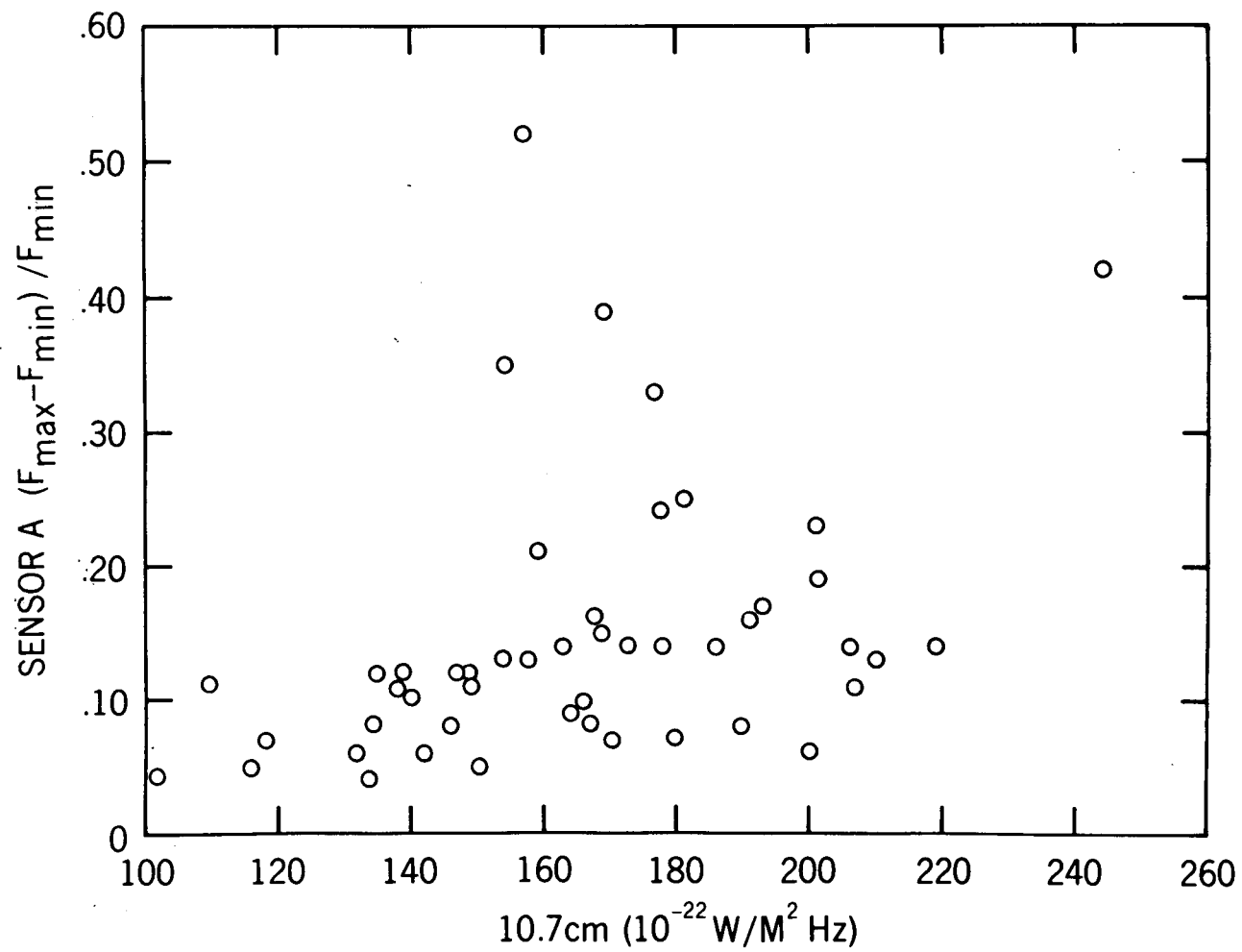


Figure 8. Comparison of MUSE sensor A enhancement with calcium plaque index A.I.).

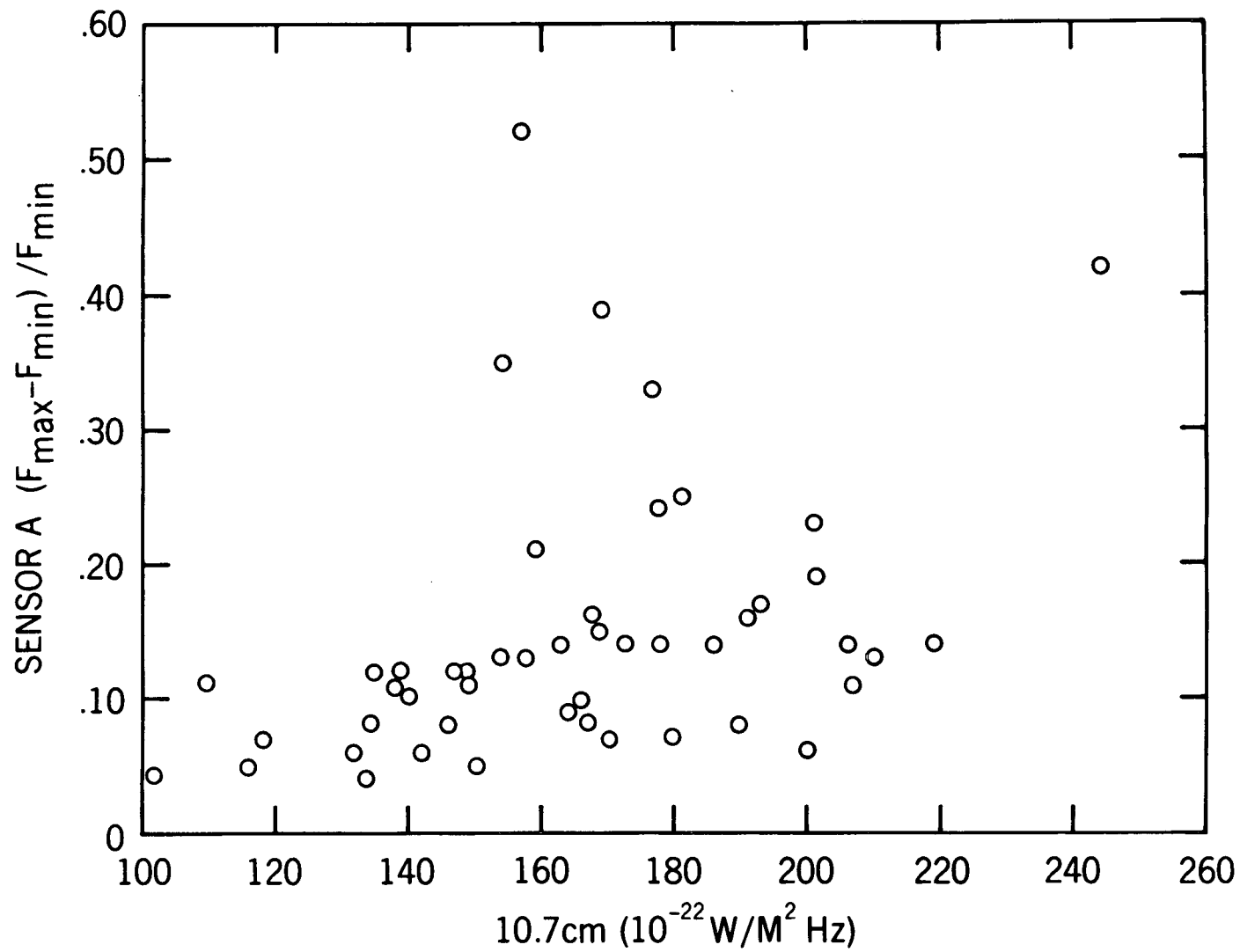


Figure 9. Comparison of MUSE sensor A enhancement with 10.7 cm flux.

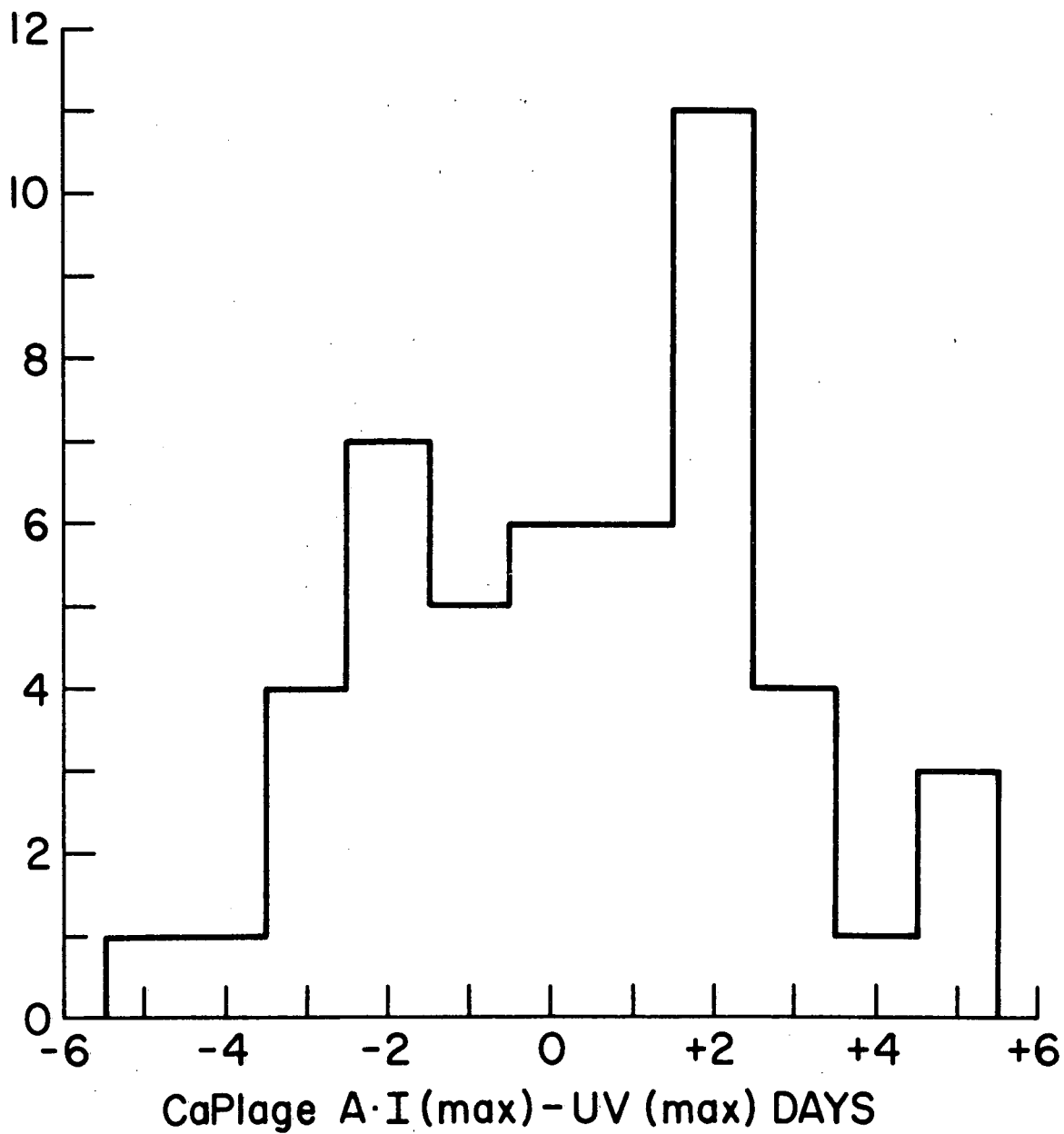


Figure 10. Time delay between maxima of calcium plage index and MUSE sensor A signal.

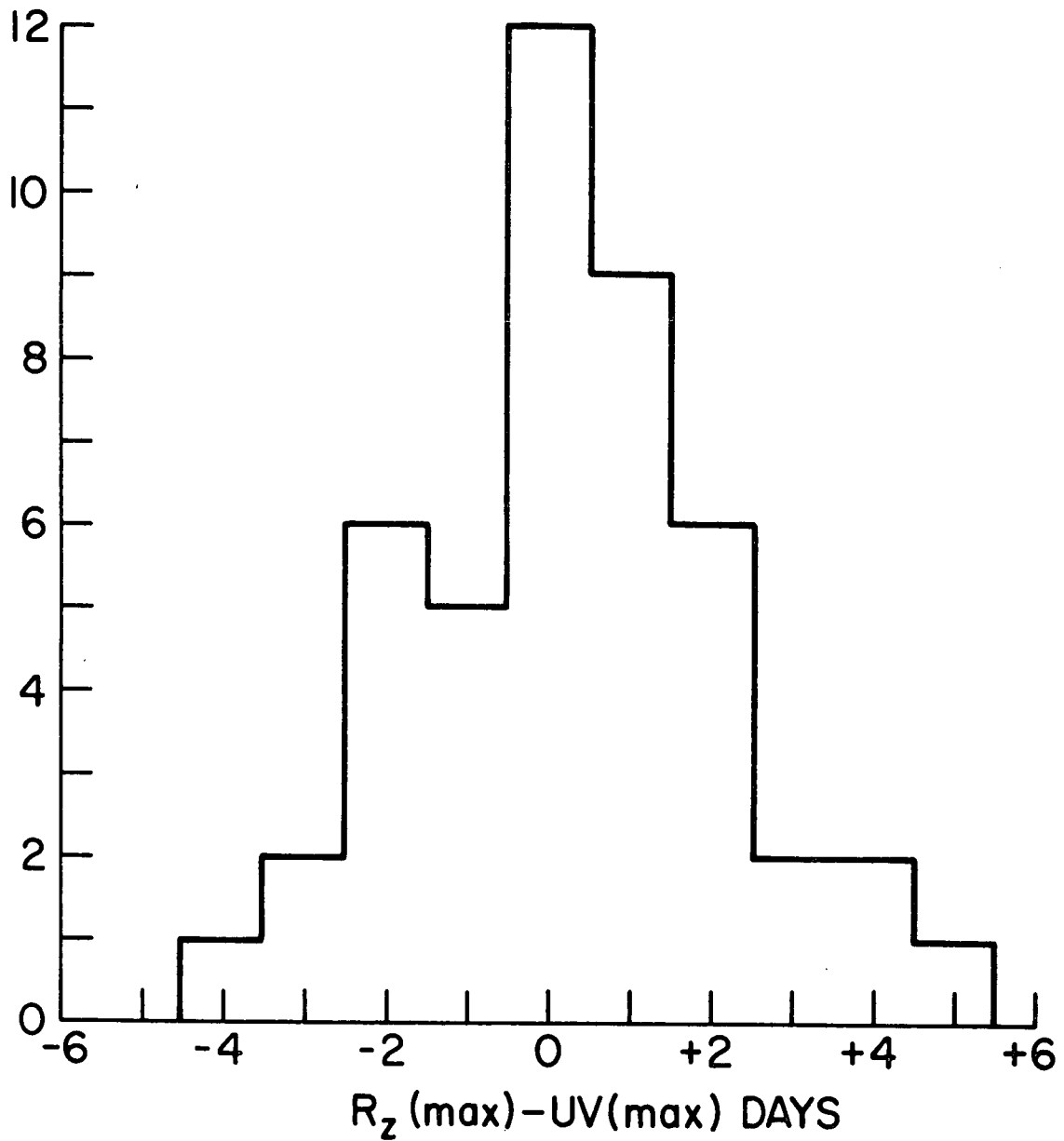


Figure 11. Time delay between maxima of provisional mean Zurich sunspot number and sensor A signal.

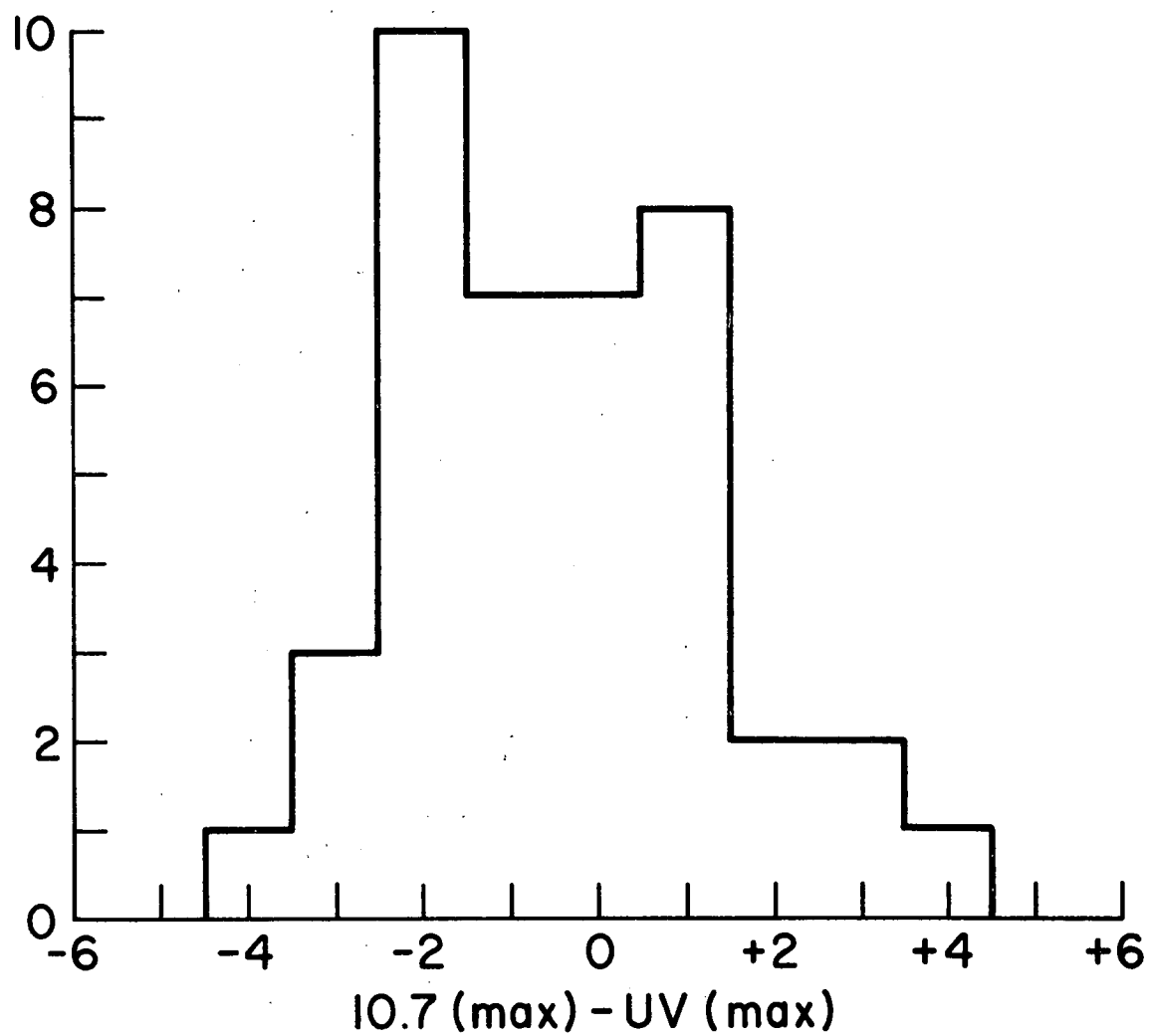


Figure 12. Time delay between maxima of 10.7 cm flux and MUSE sensor A signal.

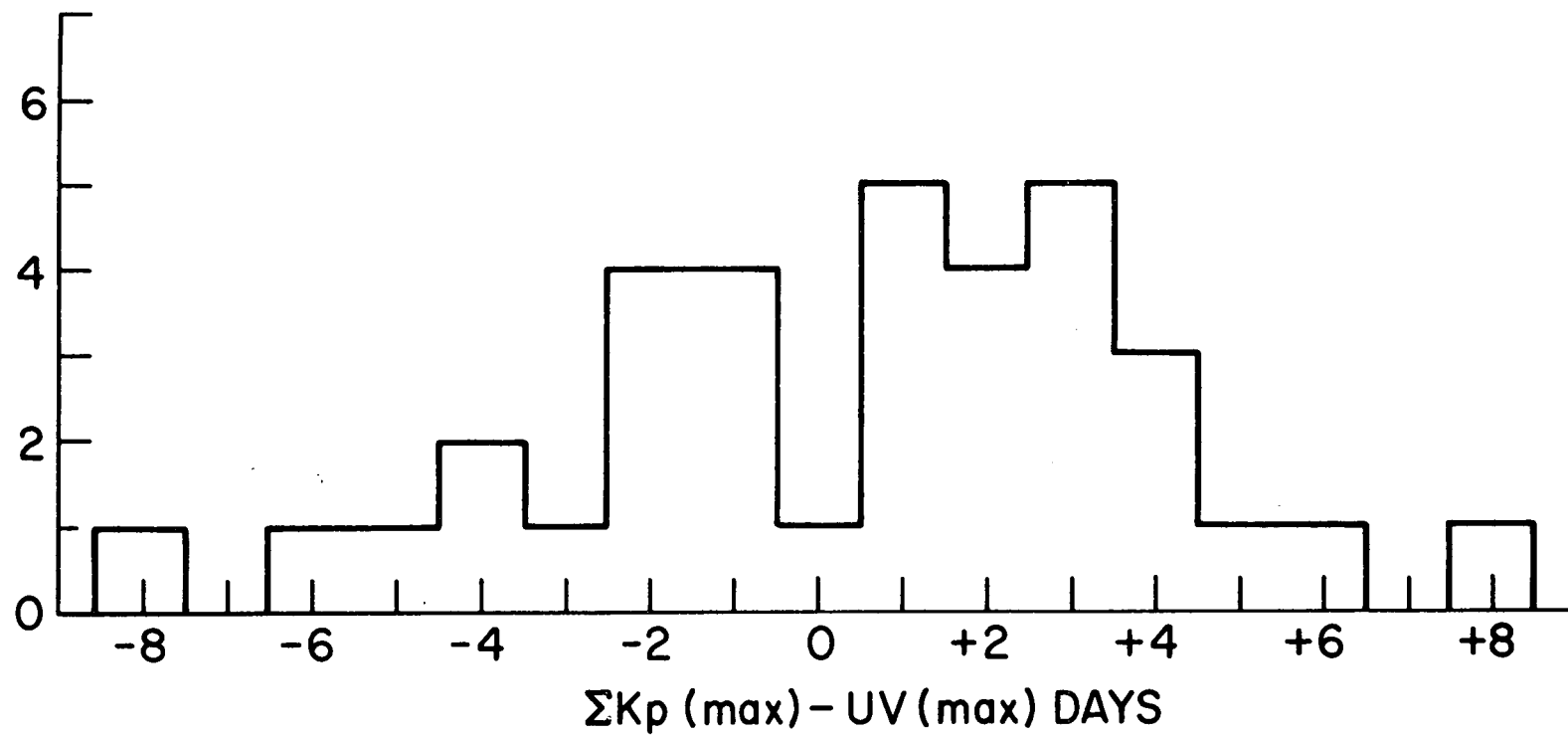


Figure 13. Time delay between maxima of daily Kp and MUSE sensor A signal.

OBSERVED UV ENHANCEMENTS IN THE SOLAR IRRADIANCE (F)

WAVE LENGTH REGION	PERIOD	$\frac{F(\text{max})-F(\text{min})}{F(\text{min})}$		F(69) / F(66)	
		FLARE	27 DAY (Rotation) ¹	22 MONTHS (?)	11 YEARS (Sunspot)
LYMAN ALPHA 1216A	$E(\%)=0.3A^{3/2}$ 16.2% class 3, OPTICAL	25%	10-30%	0.8 ²	
1750A	NONE OBS.	6%	NONE OBS.	2.44	
2900A	NONE OBS.	1%	NONE OBS.	1.52	

- ¹ OBSERVED PRINCIPALLY FROM TWO ACTIVE REGIONS ABOUT 180°
APART IN SOLAR LONGITUDE SINCE NIMBUS 3 LAUNCH APRIL, 1969
- ² PROBABLY MASKED BY 27d VARIATION

Figure 14. Summary of the observed uv enhancements of irradiance with the MUSE experiments.